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Irwin et al.

[11] **3,821,665**

[45] **June 28, 1974**

[54] **TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR**

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[52] **U.S. Cl.** ..... **331/116 R**, 331/66, 331/176

[51] **Int. Cl.** **H03b 5/36**

[58] **Field of Search** ..... 331/66, 116 R, 158, 164, 331/176

[56] **References Cited**

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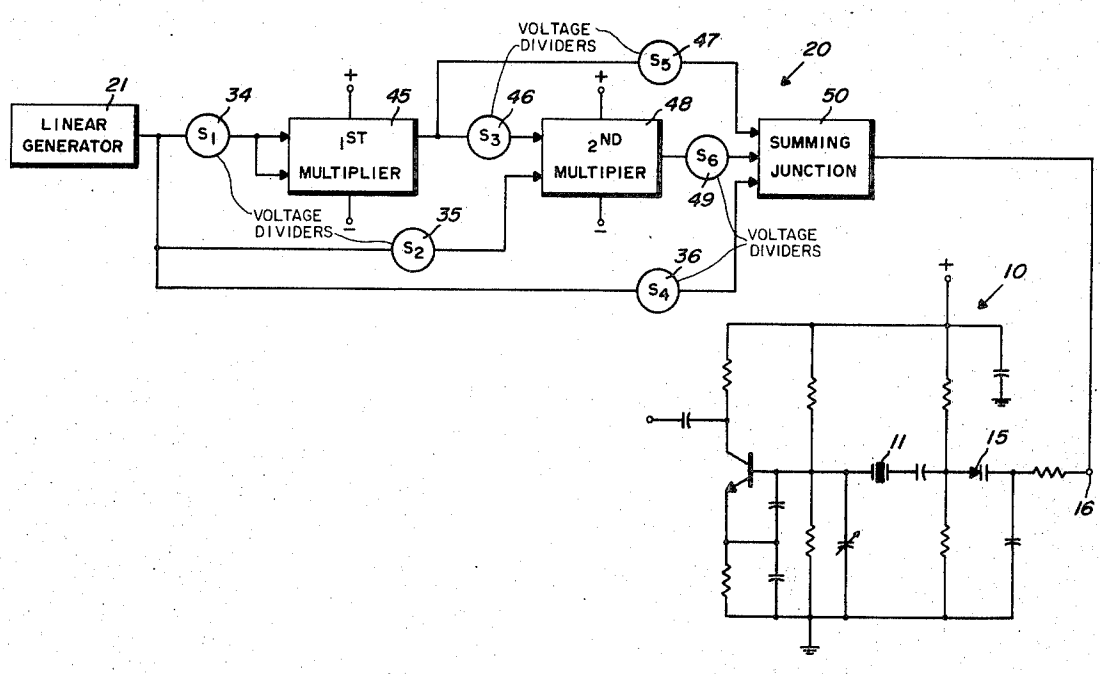
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Assistant Examiner—Siegfried H. Grimm
Attorney, Agent, or Firm—Eugene A. Parsons; Vincent Rauner

[57] **ABSTRACT**

An oscillator having a frequency determining crystal connected therein which produces a frequency deviation with temperature defined by a formula including first, second and third order terms and a varactor connected to said oscillator for varying the frequency of said oscillator in response to a voltage produced by a function generating means which produces a frequency variation of the varactor that is equal to and the inverse of the frequency deviation of the oscillator so that the total effect of temperature variations on the circuit is little or no frequency deviations with ambient temperature changes.

5 Claims, 5 Drawing Figures



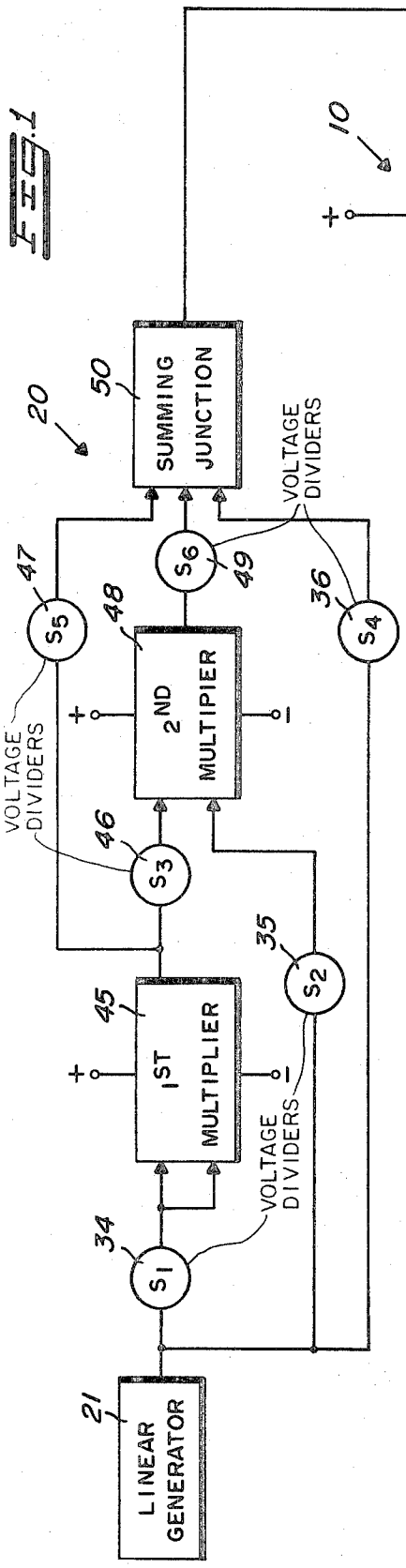
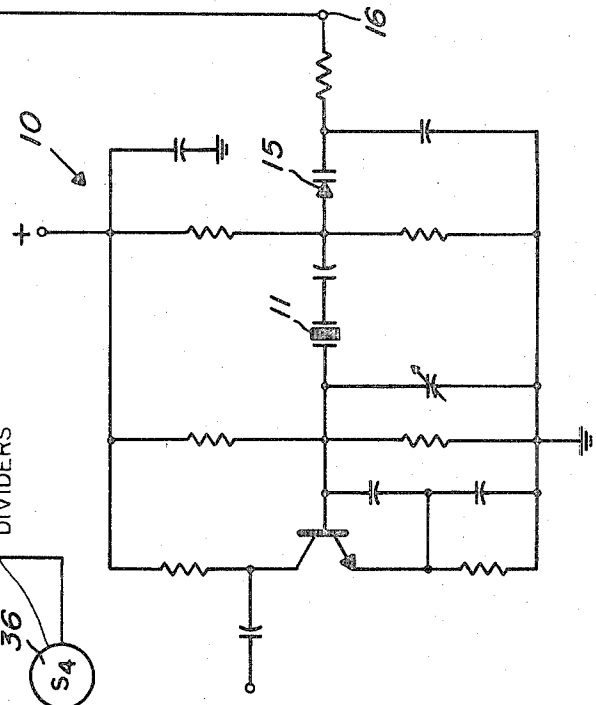

20
50
SUMMING JUNCTION
VOLTAGE DIVIDERS
47
48
49
36
S_5
S_6
S_4
2ND MULTIPIER
VOLTAGE DIVIDERS
46
S_3
35
S_2
45
1ST MULTIPLIER
VOLTAGE DIVIDERS
34
S_1
21
LINEAR GENERATOR

FIG. 1


10
15
16
11

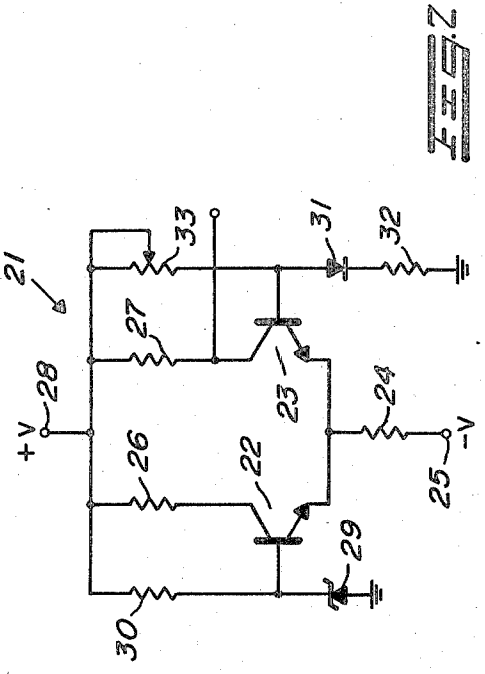

21
33
31
32
27
28
+V
23
24
-V
26
22
25
29
30

FIG. 2

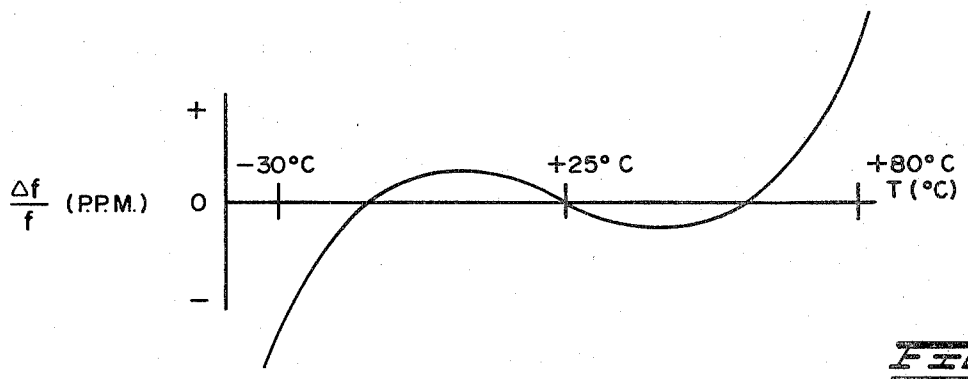


Fig. 3

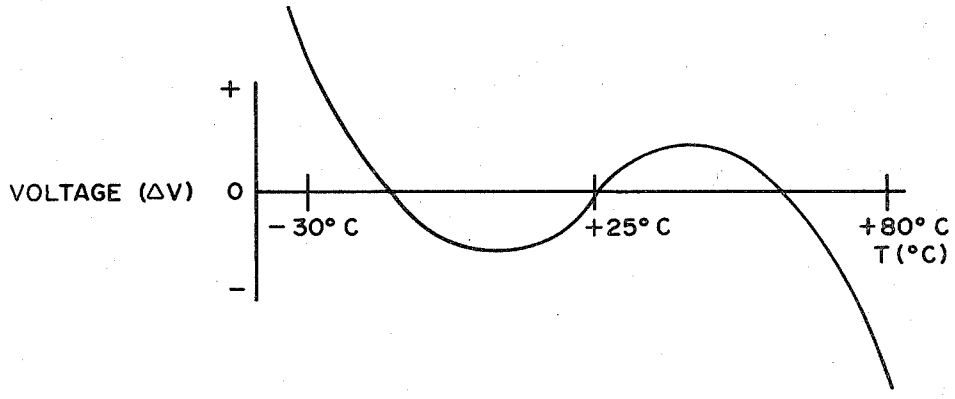


Fig. 4

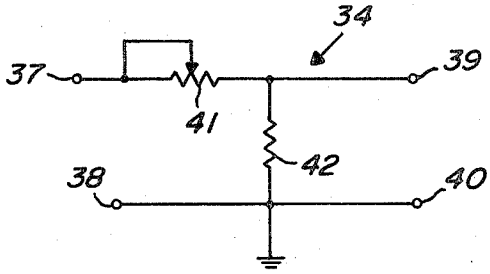


Fig. 5

TEMPERATURE COMPENSATED CRYSTAL OSCILLATOR

BACKGROUND OF THE INVENTION

1. Field of the Invention

Many circuits require oscillators which remain stable throughout predetermined temperature ranges. Frequency tolerances in the past have sometimes required an accuracy of only 10 parts per million or less. Today, however, it is frequently necessary that this accuracy be reduced to 1 or even to 0.1 parts per million and the requirement for greater accuracy is continually increasing. While the components of frequency determining means for an oscillator are chosen so that the oscillator resonates at a predetermined frequency, ambient temperature variations can and do affect the oscillator to cause frequency drift or variation. When an uncompensated quartz crystal, for example, is used as the frequency determining means, the frequency may vary from 10 parts per million to 100 parts per million over a given temperature range depending upon the angle of the cut of the crystal. Over a temperature range of − 30°C to + 80°C the frequency variations of the crystal follow a curve generally in the form of an S, which curve is defined by the following equation:

$$\Delta f/f = a(T - T_r) + b(T - T_r)^2 + c(T - T_r)^3$$

where a, b and c are coefficients which depend upon the angle of cut of the crystal, T is the temperature of the oscillator in degrees centrigrade, T_r is a reference temperature in degrees centrigrade, Δf is the frequency excursion referenced to the frequency measured at T_r and f is the crystal frequency at temperature T_r.

2. Description of the Prior Art

In prior art structures some attempts have been made to compensate for frequency variations due to temperature changes by attempting to provide a curve that is the reciprocal of the frequency drift of the uncompensated crystal with respect to ambient temperature variations. In general, these prior art devices utilize thermistors and the like having negative temperature coefficients of resistivity in complicated impedance networks. These impedance networks are generally relatively complicated to build and are extremely complicated to alter or adjust.

SUMMARY OF THE INVENTION

The present invention pertains to apparatus and methods for temperature conpensating crystal oscillators wherein a voltage variable reactance means is connected to the oscillator and function generating means are connected to the reactance means for providing a control voltage to the reactance means having a first, second and third order term therein to control the reactance means such as to have an effect on the oscillator frequency which is equal and opposite to that of temperature variations on the crystal and other oscillator components.

It is an object of the present invention to provide an improved temperature compensated crystal oscillator.

It is a further object of the present invention to provide a temperature compensated crystal oscillator including a voltage variable reactance means and function generating means supplying a control voltage to the reactance means to reduce or remove frequency variations of the oscillator due to temperature changes.

It is a further object of the present invention to provide adjustable function generating means for controlling a voltage variable reactance means so that the reactance thereof varies in a predetermined manner defined by an equation containing first, second and third order terms.

These and other objects of this invention will become apparent to those skilled in the art upon consideration of the accompanying specification, claims and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring to the drawings:

FIG. **1** is a semi-block/semi-schematic drawing of a temperature compensated crystal oscillator incorporating the teachings of the present invention;

FIG. **2** is a schematic diagram of an embodiment of a linear voltage generator;

FIG. **3** is a typical graphical representation of the frequency deviation of a crystal with temperature changes;

FIG. **4** is a graphical representation of the control voltage applied to the voltage variable reactance means to compensate for the crystal frequency versus temperature variations illustrated in FIG. **3**; and

FIG. **5** is a schematic diagram of an embodiment of a scaling factor means utilized in the function generator of FIG. **1**.

DESCRIPTION OF THE PREFERRED EMBODIMENT

Referring specifically to FIG. **1**, the numeral **10** generally designates an oscillator having a frequency determining crystal **11** connected therein. In the present embodiment the crystal **11** is an AT cut crystal which is cut at an angle of approximately 35°22′. The frequency deviation of the oscillator **10** with ambient temperature changes is depicted by the curve of FIG. **3.** The curve in FIG. **3** is defined by the equation

$$\Delta f/f = a(T - T_r) + b(T - T_r)^2 + c(T - T_r)^3.$$

It should be understood that this is a general equation which it is believed applies directly to all quartz crystals (although some terms may be zero) and may, with some minor variations, apply to other types of crystals. It should further be understood that virtually any type of oscillator may be provided which has a crystal connected therein for determining the frequency thereof and the present teachings may be utilized for providing a compensating circuit therefor.

A voltage variable reactance means, which in this embodiment is a varactor **15,** is connected to the oscillator **10** so as to vary the frequency of the oscillator **10** in response to a control voltage applied to an input terminal **16.** The frequency sensitivity of the varactor **15** is defined by the equation

$$S = \Delta f/f/\Delta v$$

where $\Delta f/f$ is the frequency deviation in parts per million (ppm) and Δv is the control voltage change applied to the varactor **15.** To compensate for variations of the oscillator **10** with temperature, the control voltage applied to terminal **16** must vary the reactance of the varactor **15** so as to have an effect on the oscillator **10** which is the inverse of crystal frequency versus temper-

ature changes. A typical control voltage versus temperature curve is illustrated in FIG. 4. This curve is defined by the equation

$$\Delta v = [K_a(T - T_r) + K_b(T - T_r)^2 + K_c(T - T_r)^3]$$

where K_a, K_b and K_c are variables the value of which is dependent upon the angle and design of crystal **11**, the specific varactor **15** used and the specific configuration of the oscillator **10**.

A function generator, generally designated **20**, is connected to the terminal **16** for supplying a control voltage thereto as depicted in FIG. 4. The function generator **20** includes a linear generator **21** which generates a voltage at the output that is linear over a predetermined temperature range. Linear voltage generators are relatively numerous and typical examples are forward biased diodes and bipolar transistor junctions, reverse biased zener diodes, and diode-resistor bridge circuits, and linearized resistor-thermistor voltage divider circuits. The output of the generator **21** is supplied to scaling factor means, which in this embodiment includes three resistive voltage dividers **34**, **35** and **36**.

Referring to FIG. **2**, a schematic diagram of an exemplary embodiment of the linear voltage generator **21** is illustrated. In this embodiment a pair of transistors **22** and **23** have common connected emitters which are connected through a resistor **24** to a terminal **25** having a negative voltage supplied thereto. The emitters are connected through a pair of resistors **26** and **27**, respectively, to a terminal **28** having a positive voltage supplied thereto. The base of the transistor **22** is connected to the cathode of a zener diode **29**, the anode of which is connected to ground and is also connected through a resistor **30** to the positive voltage terminal **28**. The base of the transistor **23** is connected to the anode of a diode **31**, the cathode of which is connected through a resistor **32** to ground and the base is also connected to one fixed terminal of a potentiometer **33**. The movable contact and the other fixed terminal of the potentiometer **33** are connected together and to the positive voltage terminal **28**. The potentiometer **33** is adjusted so that the voltage on the bases of the transistors **22** and **23** are equal at the inflection temperature, which in the present embodiment is 25°C. It will of course be understood that the inflection temperature will vary somewhat with the angle of cut of the crystal **11** but the inflection temperature variation is negligible for small variations in the angle of cut (on the order of 2 to 5 minutes) and may be assumed constant for batches of similarly cut crystals. The linear voltage output is obtained from the collector of the transistor **23** and, in this embodiment, the overall circuit is adjusted so that the linear voltage output passes through **0** when the ambient temperature of the circuit is at 25°C. The linear voltage generator will always be adjusted so that the linear voltage output thereof passes through **0** at the inflection temperature of the crystal **11**. This will insure that the compensating voltage applied to the terminal **16** will coincide with the frequency versus temperature deviation of the oscillator **10**. The resistor **24** should be large to reduce the effects of supply voltage variations or a constant current source may be incorporated in the emitter circuit.

In the present embodiment all of the resistive voltage dividers are similar and a schematic diagram of resistive voltage divider **34** is illustrated in FIG. **5** for exemplary purposes. The divider **34** includes a pair of input terminals **37** and **38** and a pair of output terminals **39** and **40**. The input terminal **38** and output terminal **40** are connected directly together and to ground. The input terminal **37** is connected to the adjustable contact and a fixed contact of a potentiometer **41**. The other fixed contact of the potentiometer **41** is connected to the output terminal **39** and to one side of a resistor **42**, the other side of which is connected to ground. By adjusting the potentiometer **41** the scale factor of the voltage input to the voltage output is adjusted so that a signal applied to the input terminals **37** and **38** can be provided with an adjustable constant component. It should be understood that other scaling factor means might be devised by those skilled in the art but the illustrated embodiment is utilized because of its simplicity and ease of adjustment.

A first multiplier **45** has a pair of inputs, which receive the signals that are multiplied together, and an output. The two inputs to the multiplier **45** are the same and both come from the resistive voltage divider **34**. Thus, the first multiplier **45** provides a second order term or the square of the linear (first order) term times a constant. Circuits such as multipliers **45** are well known in the art and are available commercially from a number of manufacturers in IC form. The output of multiplier **45** is supplied to scaling factor means including two resistive voltage dividers **46** and **47**, similar to resistive voltage divider **34**.

A second multiplier **48**, similar to multiplier **45** receives a signal on a first input from the voltage divider **46** and on the second input from the voltage divider **35**. Since the signal from the voltage divider **46** is a second order term and the signal from the voltage divider **35** is a first order term, the output of the multiplier **48** is a third order term or the cube of the linear signal from the generator **21**. The output of the multiplier **48** is applied to scaling factor means including a resistive voltage divider **49**, similar to the resistive voltage divider **34**. The various gains, if any, in the generator **21** and the multipliers **45** and **48**, the amount of voltage change with a unit change in temperature in the generator **21** and the scale factors S_1, S_2 and S_3 or adjustments of the voltage dividers **34**, **35** and **46** are all arbitrary except that each of these factors must be set so that each of the inputs and outputs of the various circuit components do not exceed performance restrictions. The various gains and adjustments mentioned above may be fixed for any specific design.

A summing junction or circuit **50** has three inputs and an output. The summing junction **50** may be any well known resistor network or other circuit which provides a signal at the output that is the sum of the three signals at the input thereof. The output terminals of the voltage dividers **36**, **47** and **49** are connected to the three inputs of the summing junction **50**. Thus, the first input terminal of the summing junction **50** receives a linear or first order term multiplied by a constant K_1, which is supplied by the voltage divider **36**. The second input of the summing junction **50** receives the square or second order term multiplied by a constant K_2, which is supplied by the voltage divider **47**. The third input of the summing junction **50** receives the cube or third order term multiplied by a constant K_3, which is provided by the voltage divider **49**. The summing junction **50** adds the three terms together to provide a voltage at the output which is defined by the equation

$$\Delta v = -[K_1(T - T_r) + K_2(T - T_r)^2 + K_3(T - T_r)^3]$$

where K_1 is the constant adjusted by the voltage divider **36**, K_2 is the constant adjusted by the voltage divider **47** and K_3 is the constant adjusted by the voltage divider **49**. The output of the summing junctions **50** is connected to the input terminal **16** of the oscillator **10**.

Utilizing the equation for the frequency sensitivity of the varactor **15** and substituting the equation for Δv, an equation can be written for the frequency variations of the oscillator **10** due solely to the control voltage applied to the varactor **15**. The equation is

$$\Delta f/f = -S[K_1(T - T_r) + K_2(T - T_r)^2 + K_3(T - T_r)^3]$$

where K_1, K_2 and K_3 include the various fixed and arbitrary constants previously mentioned and variable or adjustable constants determined by voltage dividers **36, 47** and **49**, respectively, as set forth in more detail below.

$$K_1 = K_z S_4$$

$$K_2 = (K_z S_1)^2 K_{M1} S_5$$

$$K_3 = (K_z)^3 S_1^2 S_2^2 S_3 S_6 K_{M1} K_{Mz}$$

where:

$K_z = \Delta V$ (volts)/ΔT (°C) for the output of generator **21**

S_1, S_2, S_3, S_4, S_5 and S_6 are the scale factors of the resistive voltage dividers **34, 35, 46, 36, 47** and **49**

K_{M1} and K_{Mz} are the gains of the multipliers **45** and **48**

Since the Δf/f of the oscillator **10** produced by the varactor **15** must be equal and inverse to the curve illustrated in FIG. **3**, the constants K_1, K_2 and K_3 must be adjusted so that their amplitudes are equal to the constants *a*, *b* and *c* (of the equation defining the curve illustrated in FIG. 3). To accomplish this with a minimum amount of effort, the summing junction **50** is disconnected from the terminal **16** and the frequency deviation at the output of the oscillator **10** is measured at three different temperatures other than the inflection temperature (at which the output frequency deviation is 0). Since the frequency sensitivity, *S*, of the varactor **15** is known or can be measured, it is only necessary to write three equations and solve for the three unknowns, K_1, K_2 and K_3 after which the voltage dividers **36, 47** and **49** can be adjusted to provide these constants. The output voltage Δv of the summing junction **50** is similar to that illustrated in FIG. **4** and, when multiplied by the frequency sensitivity, *S*, of the varactor **15** will be equal to and the inverse of the curve illustrated in FIG. **3**.

Thus, the function generator **20** and varactor **15** accurately compensate the output frequency of the oscillator **10** for variations in ambient temperature so that the output of the oscillator **10** is extremely temperature stable. Further, the function generator **20** is relatively simple to adjust since there are only three variables, voltage dividers **36, 47** and **49**, and only three relatively simple measurements of the frequency deviation at the output of the oscillator **10** need be made to adjust the function generator **20**. Although third order equations have been used throughout the description for exemplary purposes, it should be understood that more complicated equations, including higher order terms, might be involved. In these instances additional multipliers and scale factors can be added to obtain these higher order terms in accordance with the teachings herein.

While I have shown and described a specific embodiment of this invention, further modifications and improvements will occur to those skilled in the art. I desire it to be understood, therefore, that this invention is not limited to the particular form shown and I intend in the appended claims to cover all modifications which do not depart from the spirit and scope of this invention.

We claim:

1. A temperature compensated crystal oscillator comprising:

a. an oscillator having a frequency determining crystal connected therein;

b. voltage variable reactance means connected to said oscillator for varying the frequency of said oscillator in response to a voltage applied to said reactance means;

c. generating means providing a voltage which varies linearly with temperature;

d. first multiplying means coupled to said generating means for providing a voltage which is the square of the voltage from said generating means;

e. second multiplying means coupled to said generating means for providing a voltage which is the cube of the voltage from said generating means; and

f. summing means coupled to said generating means, said first multiplying means, said second multiplying means and said voltage variable reactance means for supplying a voltage to said reactance means proportional to the sum of the voltages from said generating means and said first and second multiplying means.

2. A temperature compensated crystal oscillator as claimed in claim **1** including in addition three scaling factor means coupling the generating means and the first and second multiplying means to the summing means, respectively, for providing the linear, square and cube voltages each with a predetermined amplitude to provide a sum voltage which controls the reactance means to vary the frequency of the oscillator the inverse of variations of the oscillator due to temperature changes thereof.

3. A temperature compensated crystal oscillator as claimed in claim **2** wherein the scaling factor means each include variable means for varying the output amplitude of voltages applied thereto.

4. A temperature compensated crystal oscillator as claimed in claim **1** wherein the crystal is an AT cut quartz crystal.

5. A temperature compensated crystal oscillator comprising:

a. an oscillator having a frequency determining crystal connected therein;

b. voltage variable reactance means connected to said oscillator for varying the frequency of said oscillator in response to a voltage applied to said reactance means; and

c. function generating means connected to supply a control voltage to said reactance means for varying the frequency of said oscillator inversely to variations in the frequency of said oscillator caused by variations in temperature of said oscillator, said function generating means including a linear generator and at least one multiplier for producing higher order terms proportional to the frequency variations of said oscillator due to the variations in temperature of said oscillator.

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